SNOW AND ICE CONTROL WORKING GROUP

THE PHYSICS OF SNOW AND ICE CONTROL ON ROADS AND HIGHWAYS

Kathleen Hanley

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TABLE OF CONTENTS

Page

ABSTRACT i

INTRODUCTION 1

ICE 1-2

SNOW 2-3

HOW CHEMICALS MELT ICE AND SNOW 3-6

FACTORS WHICH INFLUENCE MELTING:

(a) Temperature 6

(b) Traffic 6-7

(c) Radiation Processes 7

(d) Humidity 7

(e) Wind 7

(f) Type of Road Surface 8

(g) Topography 8

MATERIALS USED FOR SNOW AND ICE CONTROL:

(a) Sodium Chloride 8-10

(b) Calcium Chloride 10-11

(c) Mixtures 11

(d) Liquids 11

(e) Abrasives 12

(f) Mixtures of Chlorides and Abrasives 12

OTHER SOLUTIONS 12-13

MINIMIZING SALT USE 13-14

REFERENCES 15

ABSTRACT

This study examines the properties of chemicals used to weaken the bond between the pavement and snow or ice, the physical process of melting, and the factors which influence the effectiveness of current techniques for winter road maintenance. It is found that the amount and type of material used should be much more closely associated with prevailing weather conditions, timing of application being of great importance.

1. INTRODUCTION

At present chemicals, ploughs, and abrasives are most commonly used for winter road maintenance. Chemicals are applied to weaken the bond between the snow or ice and the pavement and to prevent the formation of ice and compacted snow. Ploughs are used to remove snow accumulations. Abrasives are spread to provide traction.

By far the most widely used material for snow and ice control is sodium chloride (NaCl) in the form of rock salt. In order to obtain bare pavement as soon as possible, immense quantities of this chemical are spread on roads every winter. The resulting high costs and damaging side effects make it necessary to minimize the use of NaCl through more efficient application and at the same time to search for alternatives.

This paper deals mainly with the properties of chemicals and abrasives, and the external factors which influence their action. To complete the picture the mechanism by which chemicals are able to melt snow and ice is outlined. An understanding of the physics of the system used to combat winter precipitation and the role which external variables play, facilitates more efficient use of these materials and provides a background for evaluation of possible alternatives.

2. ICE

The four types of ice which are commonly found on roadways and bridges are glare ice, snow glaze, hoarfrost and icings.

Glare ice forms when rain or drizzle, usually supercooled, falls on a cold pavement whose temperature is at or below freezing. This creates a uniform, tightly bonded sheet of ice which is very difficult to remove. The air temperature is usually between 25°F (-4°C) and 32°F (0°C) when this occurs.

More common than glare ice is snow glaze, which is snow which has turned into ice. This ice is dense and adheres strongly to the pavement making it equally difficult to remove. Traffic can create snow glaze by its compressing and melting action. This ice is often found at intersections and on hills or bridges where vehicles stop and start or spin their wheels. Snow glaze can also form when snow melts due to a rise in ambient temperature or absorption of solar radiation and then refreezes when the temperature falls.

Hoarfrost forms when a pavement cools down below $32^{o}F$ ($0^{o}C$) as it radiates energy to a clear night sky. Water vapour in the air condenses on the pavement then freezes provided that the heats of condensation and fusion can be dissipated without bringing the temperature of the road above freezing. This ice is comparitively easy to remove as it forms as separate particles, like little spheres stacked together, and hence is weakly bonded to the pavement. Bridges are particularly susceptible to hoarfrost formation since they lose heat from their lower surface to the air below them as well as from their upper surface. They have no heat reservoir in the underlying ground as pavements do.

Icings are potentially the thickest variety of ice which is found on roadways. It results from the freezing of water, such as roadside seepage or meltwater, which has flowed onto the pavement.

3. SNOW

Freshly fallen snow is composed of ice crystals, air and perhaps some water. It is formed when water droplets in a cooled air mass freeze to form ice crystals. These fall to the ground as snow flakes when sufficiently heavy. When the atmospheric temperature is low, the air can hold little moisture and snow is usually dry and loose. In warmer weather the air's high moisture content gives rise to larger snowflakes and denser, wetter snow. After snow has fallen, its density increases with time. Traffic makes snow denser by pushing air from it and melting it.

The properties of snow which are relevant to its removal are its density and water content. Dense snow will be heavy and hence hard to remove mechanically. Because density increases after snow has fallen, it should be removed as soon as possible. Early removal also prevents the snow from forming a strong bond with the pavement as ice does.

The water content is important because less heat is required to melt wet snow than dry snow. This can be seen by noting that 76.4 calories of heat energy are needed to melt 1 g of ice at atmospheric pressure, whereas only 1 calorie is required to raise the temperature of water at 15°C by 1°C.

4. HOW CHEMICALS MELT ICE AND SNOW

Discussion is limited to how chloride salts* melt ice and snow since they are the chemicals most commonly used for this purpose. Most aspects of the melting process can be generalized to other chemicals used for melting winter precipitation.

When particles of NaCl or $CaCl_2$ are spread on ice and snow they dissolve to form a pocket of salt solution provided there is enough water available in the air or surrounding precipitation. Dissolving is the dissociation of the salt ions in water as they are surrounded by water molecules attracted by coulombic forces.

$$\text{NaC} + \text{Water} \longrightarrow \text{Na}^{+} + \text{Cl}^{-}$$

$$\text{CaCl}_2 + \text{Water} \longrightarrow \text{Ca}^{++} + 2\text{Cl}^{-}$$

The polar nature of water makes it an excellent solvent for ionic substances such as NaCl and $CaCl_2$.

NaCl has no ability to attract and absorb moisture, (non-deliquescent) so that if there is none readily available it will not dissolve. The solution of NaCl is slightly endothermic. $CaCl_2$ on the other hand is highly deliquescent and usually goes into solution immediately. The dissolving of $CaCl_2$ is exothermic.

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*Both $CaCl_2$ and NaCl are chemically "salts".

After a pocket of aqueous solution forms, it melts nearby ice and snow becoming more and more dilute. Heat must be available from the surrounding ice and snow, air or pavement for any melting to occur. Melting ceases when the solution is sufficiently dilute to remain in equilibrium with the rest of the ice and snow at the system temperature.

Thus we see that if water contains dissolved NaCl or $CaCl_2$, it can remain in liquid form at temperatures below 32°F (0°C). This phenomenon is best analyzed in terms of vapour pressure: Water molecules in a liquid are constantly leaving and rejoining it at the surface. At equilibrium the rate of leaving and returning is fixed, giving rise to a well defined vapour pressure, determined mainly by temperature. The reason that aqueous solutions of chloride salts are liquids below 32°F is that they have a lower vapour pressure than pure water does at a given temperature. This is illustrated in figure 1.

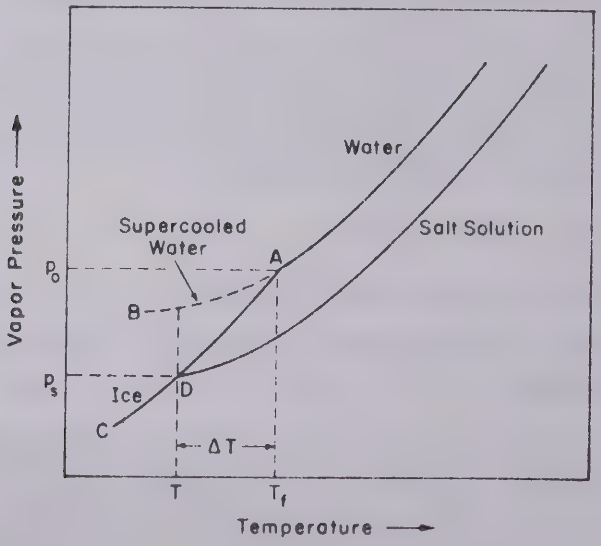

FIGURE 1*

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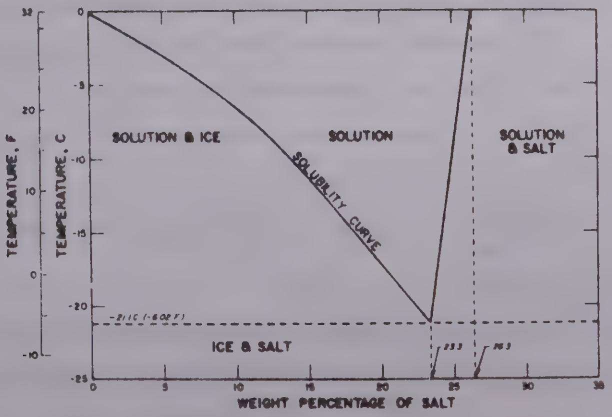
* National Research Council, Minimizing de-icing chemical use, Transportation Research Board, 1974: page 3.

Cooling water corresponds to moving along the upper curve to point A at T_f, the freezing point of water. Here the vapour pressures of the solid and liquid phases of water are the same and they can co-exist in equilibrium. If the system is now cooled further it can move along the dotted line. This represents supercooling and will occur if the water is very pure. Normally, the water freezes completely to ice at T_f because water vapour supplied by the liquid condenses to form ice at a faster rate than molecules leave the existing ice. Any further cooling lowers the vapour pressure of the ice pronouncedly as shown in the diagram.

Now consider cooling a salt solution. This is represented by the lower curve in figure 1. When the system reaches T_f, the vapour pressure of the salt solution is lower than that of ice. Hence no freezing occurs until B at temperature T. When the vapour pressures of solution and ice are equal. Further cooling results in ice formation as above. The freezing point of the salt solution is thus lower than T_f by an amount ΔT, the freezing point depression. This lowering of the freezing point occurs only up to a point however.

The capacity of chloride salts to lower the freezing point of water is best illustrated on a phase diagram. Figure 2 below is a simplified version of the phase diagram for pure sodium chloride.*

FIGURE 2**



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* for more accurate phase diagram see Kaufmann Page 548.

** National Research Council, Minimizing Deicing Chemical Use, Transportation Research Board, 1974, Page 5.

The solid curve shown depicts the freezing curve for a saturated solution of sodium chloride as a function of salt concentration and temperature. We see that as salt is added to water, the freezing point of the solution lowers until the concentration is 23.3% NaCl by weight. After this point, called the eutectic, any further addition of salt raises the freezing point. The eutectic temperature of pure sodium chloride is -21.12°C or -6.02°F. This is the lowest temperature that an aqueous solution of NaCl can reach. The phase diagram for $CaCl_2$ is similar to that for NaCl although the eutectic of $CaCl_2$ is much lower, occurring at -50.6°C or -58.5°F at a concentration just above 30%.

Clearly it would be a waste to exceed eutectic concentrations when salting roads.

5. FACTORS WHICH INFLUENCE MELTING

In determining the amount and type of chemical to apply at a given location, the following must be considered: (a) temperature, (b) traffic, (c) radiation processes, (d) humidity, (e) wind, (f) type of road surface and (g) topography. These factors determine the amount of heat and moisture that is available to the system and hence affect the rate of melting.

(a) Temperature:

Warm temperatures will provide heat for melting from both the air and pavement. Pavement temperature is very important in determining available heat. If previous weather was warmer the pavement will retain heat for some time after air temperatures have cooled down. If, however, the weather was colder prior to the precipitation, the pavement can be cooler than the air and be of little help in melting. Dropping temperatures can cause melted snow and ice to refreeze on the roadway.

(b) Traffic:

Traffic helps melt snow and ice by providing heat from tire friction, pressure and the vehicles themselves. Since water is denser than ice, an increase in pressure will melt ice near 0°C, although this effect is not pronounced. Traffic also aids melting by mixing chemicals in with snow. Its weight and motion help break up ice. Traffic aids in removal as well by throwing slush and broken ice from the road. Note, however, that traffic can exert a negative influence as well by aiding the formation of packed snow if snow is not removed soon after it falls. Chemicals can be swept from the road by fast moving traffic.

(c) Radiation Processes:

Pavement exposed to the sun can be significantly warmer than the air. According to the National Research Council (14), the difference between air and pavement temperatures can be as high as 10°F (5.5°C). During the day snow and ice can also absorb solar radiation and are often warmer than the air. According to Dorsey (6), the sun can produce melting on the surface of snow even when ambient temperatures are as low as 14°F (-10°C) . Cloudy or foggy weather reduces solar absorption so that the temperatures of the snow or ice and air will be about equal. During the night the pavement will radiate energy to a clear sky. This can cause the pavement temperature to fall considerably.

(d) Humidity:

High humidity aids melting if solid chemicals are applied by providing moisture for dissolution. Low humidity poses a greater problem when using NaCl than $CaCl_2$ because of the latters' delinquescent nature mentioned previously. According to Scotto (17), solid $CaCl_2$ will not dissolve if the ambient humidity is less than 40%, NaCl will not if it is less than 70%.

(e) Wind:

Wind removes heat from the snow or ice surface as it blows over and in this way slows down melting. It reduces any temperature difference between the air and precipitation surface caused by solar absorption. It can also sweep chemicals off the road after they have been applied. However, wind also often serves as a natural snow clearer by blowing snow from the road. Chemicals spread during windy weather can hinder this process by producing a wet pavement.

(f) Type of Road Surface:

Both concrete and asphalt surfaces have their advantages. Concrete gives up its heat more quickly than asphalt but asphalt absorbs more solar radiation.

(g) Topography:

Topography which shades regions of roads hinders melting by reducing absorption of solar radiation. The longer the road is shaded from the sun during the day the less it will warm up to aid in melting. This phenomenon can create the hazard of ice patches in the shadow.

6. MATERIALS USED FOR SNOW AND ICE CONTROL

According to Keyser (12), the following properties are desirable in a de-icing material: It must be an effective melter at winter temperatures, be able to break the bond between the snow or ice and pavement, be available in large quantities and at reasonable cost, and be easy to store, handle and apply. It must not be toxic to people, animals or plants or harm metal, pavement or clothing.

At present sodium chloride and calcium chloride satisfy more of these criteria than do any other chemicals considered to date.

(a) Sodium Chloride:

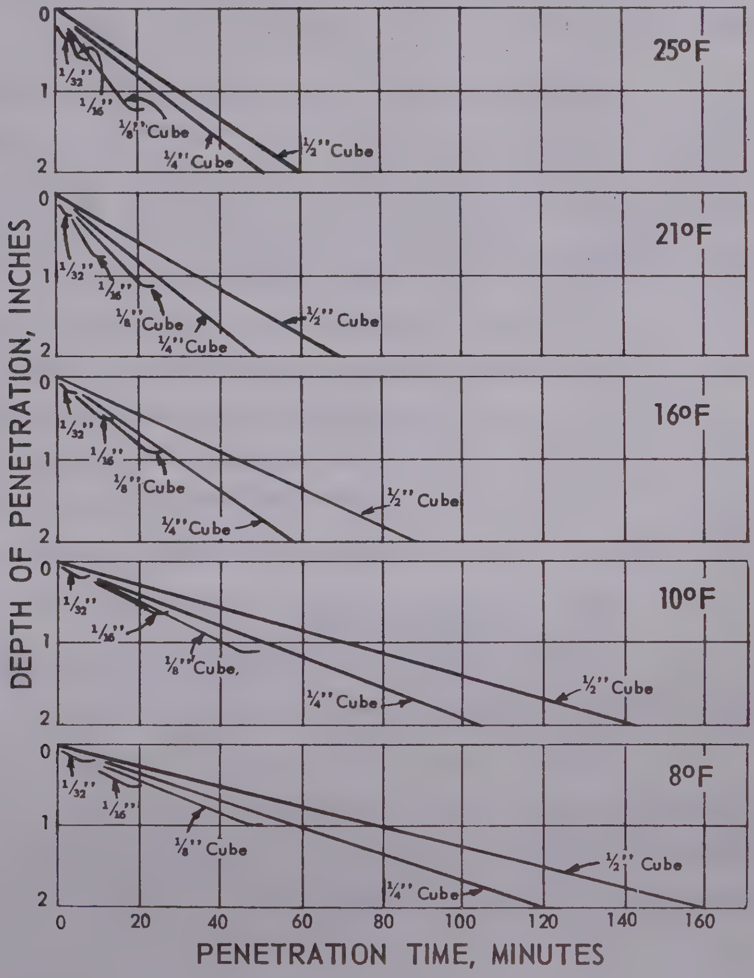
The most popular chemical de-icer is sodium chloride in the form of rock salt. Its purity usually ranges from 94-97%. The impurities are mostly chlorides, sulphates, calcium and magnesium. The procedure for the sampling and analysis of rock salt is outlined in Chapter 15 and 16 of Kaufmann (10).

Sodium chloride with its eutectic at $-6.02^{\circ}F$ is especially effective at warm temperatures above $25^{\circ}F$, its efficacy decreasing as the ambient temperature drops to $10^{\circ}F$, below which it cannot be used alone because prohibitively high concentrations would be required. Nevertheless NaCl is widely used because precipitation during the winter usually occurs within its melting range. It is particularly favoured because it is relatively inexpensive.

Rock salt used for melting should be a well graded mixture containing a range of grain sizes. According to Kaufmann (10), the particles should be passed by Tyler sieve No. 3 and retained by No. 12.

For very cold weather a coarser grade may be used. Large particles in the mixture serve initially as a traction aid before they bore their way down through the ice or snow layer to the pavement. The pocket of brine which they have carried with them then diffuses outward over the pavement to meet the brine formed by adjacent particles. In this way the bond between the snow or ice and road surface is weakened. Smaller grains penetrate faster and less far than the large grains. They help mitiate the melting action because they dissolve more quickly. The penetration of different grain sizes is illustrated in figure 3.

FIGURE 3*



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* Salt Institute, Technical Analysis of Salt for Snow and Ice Removal, 1962; Appendum.

The depth of penetration is approximated as a linear function of time. This is somewhat simplistic but is reasonable in light of the opposing tendencies of quicker penetration as a particle becomes smaller and slower penetration as its surrounding brine becomes increasingly diluted. Thus the mixture must contain grains large enough to penetrate to the pavement and must not include particles that are so small that they dissolve only at the surface and make it slippery.

Note that when salt is applied to snow or ice it is not intended to produce complete melting. In the case of ice, it weakens the bond with the pavement allowing traffic to break up the ice and move it from the road. The addition of salt to snow produces a mealy or slushy consistency which cannot be compacted by traffic and is readily removed by ploughs and moving vehicles.

Prewetting NaCl with liquid $CaCl_2$ produces faster melting and allows the rock salt to adhere to the snow or ice thus reducing blow off by traffic or wind. The $CaCl_2$ also extends the range of effectiveness of rock salt to lower temperatures. Prewetted rock salt can be used in smaller quantities than can untreated.

When salt is spread as a preventative treatment it should cover the whole road surface. If applied after snow or ice has accumulated it is more efficient to windrow the solid in a thin strip along the centre or elevated part of the roadway. This exposes the pavement to the sun's radient heat as early as possible and produces a concentrated brine which can flow out over the pavement.

(b) Calcium Chloride:

Calcium chloride is available as both pellets and flakes. The former are about 95% pure $CaCl_2$, the latter about 77-80%.

$CaCl_2$, with its low eutectic, is usually used to melt ice and snow below $10^{\circ}F$ ($-12^{\circ}C$) when salt is no longer effective. Its efficacy as a melter decreases as the temperature drops to $-30^{\circ}F$ ($-34^{\circ}C$) below which it cannot be used.

When $CaCl_2$ is spread on ice or snow, it produces very quick melting because of its deliquescence and exothermic solution mentioned above. However, because of this, solid particles do not have the tunneling capacity of rock salt and melting occurs at the surface.

The fact that $CaCl_2$ is from two to four times more expensive than NaCl explains why it is not more widely used. Another drawback is that its hydrophillic nature prolongs drying of the pavement after precipitation has been melted. It also produces a slick and slippery surface when wet (after the melt).

(c) Mixtures:

Mixtures of chloride salts can be very effective, for the constituents have complementary properties. By providing heat and moisture by its quick, exothermic solution $CaCl_2$ facilitates fast dissolving of NaCl serving as a catalyst for the latter's longer lasting melting action.

These mixtures are usually used at lower temperatures down to $0^{o}F$ ($-18^{o}C$). As the temperature drops, the relative amount of $CaCl_2$ should increase. Chloride mixtures share the high cost and wet pavement disadvantages of $CaCl_2$.

(d) Liquids:

Aqueous solutions of chloride salts can be very effective for melting small accumulations of ice and snow and as a preventative measure.

They are able to melt precipitation more quickly and completely because they sidestep the dissolving process and make better more even contact with the pavement or snow/ice surface. There is also no problem with blow off by wind or traffic. They can be used even when the humidity is low. For these reasons less chemical is required when liquids are used.

Solutions cannot be used to melt thick accumulations of ice or snow since they lack the tunneling action of granular chemicals.

(e) Abrasives:

Abrasives such as sand, cinder and slag are used to provide traction on icy or snow covered roads. They are applied primarily on trouble spots and at low temperatures when salt cannot be used alone. They provide no melting action, do not prevent snow and ice from building up, and can in fact insulate snow and ice from the sun. They are expensive and must be spread in greater quantities than chemicals.

A problem with abrasives is that they are easily swept off the road. Thus, they should not be applied during high winds or heavy traffic. This tendency to blow off can be allayed somewhat by treating the abrasives with a small quantity of salt or prewetting them with $CaCl_2$. This allows the abrasive particle to embed itself in the surface due to the slight melting action of the chemical. Since abrasives are usually used at low temperatures, prewetting with $CaCl_2$ is preferred. Spraying also effects more abrasive particles than does mixing with salt. The surface of snow on which treated abrasives are spread must be reasonably hard. Otherwise, the abrasive would penetrate below the surface due to the chemicals melting and cease to provide any traction.

(f) Mixtures of Chemicals and Abrasives:

Mixtures of abrasives and de-icing chemicals are applied to provide melting action as well as to increase traction. They are generally used at low temperatures on low priority roads and trouble spots. Mixtures of coarse graded rock salt and sand are commonly used. The salt must be coarse graded so that a minimal amount of abrasive is carried below the snow/ice surface. Solid $CaCl_2$ can be mixed in with the salt and sand or the mixture can be prewetted with $CaCl_2$ in order to set off the melting at low temperatures.

7. OTHER SOLUTIONS

There are many alternative methods for snow and ice control which are being investigated. A few of these will be considered. For a more thorough discussion see Keyser (11).

Research is currently being carried out into the use of metranol and calcium magnesium acetate as de-icer (7). These chemicals are less expensive and can be used at lower temperatures than rock salt and they are non-corrosive.

The bond between the pavement and snow or ice can be weakened by adding chemicals directly to the pavement. A product of this type is Verglimit, which is an asphaltic mixture which is currently being tested, containing a small quantity of calcium chloride. According to Johannes (9) it should only be used on roads with daily traffic of at least 5,000 vehicles. It is intended for trouble spots where it can supplement usual chemical applications.

Alternative types of paving mixtures are being studied. The addition of rubber to asphalt has been found by Cook (4) to create a slightly flexible road surface which allows cars to weaken ice formations.

Snow and ice can be melted very effectively by heating the pavement rather than applying chemicals. However, no economically feasible system has as yet, been developed for use on a large scale.

8. MINIMIZING SALT USE

Until suitable alternatives can be found, the use of large quantities of rock salt for winter maintenance seems unavoidable. However, the amount of sodium chloride spread on roads at present can be reduced:

I. An important step in this direction is early application. This presupposes more accurate weather forecasts geared to road conditions and readily available to clearance crews.

II. Use should be made of other materials such as aqueous solutions of chloride salts, chloride mixtures, and in particular, rock salt prewetted with $CaCl_2$. Abrasives and sand-salt mixtures should be applied when possible.

III. In general, the amount and type of material should be more finely tuned to prevailing conditions. Currently, standard application rates are used to cover wide ranges of weather conditions and precipitation types. Appropriate applications should be determined empirically by testing different types and amounts of materials under various field conditions.

IV. A known amount of chemical or abrasive can be applied with calibrated vehicles equipped with automatic ground speed controls.

V. Solids should be windrowed except when used preventatively.

VI. Ploughing and other mechanical means should be relied on more extensively.

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